# Invisible Decay of Positronium to Search for Extra Dimensions

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Some theories of “Beyond Standard Model” physics postulate the existence of additional spacetime dimensions. In general, such extra-dimension theories fall into two broad classes: those with compactified extra dimensions, and those with extra dimensions of infinite extent.[1] These extra dimensions are extremely weakly coupled (only via gravity) to the usual (3+1) spacetime dimensions. One experimental signature of such physics would be the disappearance of energy from a closed system, as it coupled to gravitons which propagate in the extra dimensions.

We have made a feasibility study of a “missing energy” experiment on positronium (Ps), the bound state of an electron and positron. The experiment seeks to detect the decay rate for the process (ortho-Ps→ “nothing”). This rate can be compared with the usual decay mode of (ortho-Ps→ 3γ), with a decay rate of $\lambda = 7.04\ \mu s^{-1}$ . Previous searches for the decay mode (o-Ps→ ”nothing”) establish the current lower limit for the branching ratio BR = λ(o-Ps→ “nothing”)/λ(o-Ps→ 3γ) < 3 x $10^{-6}$.[2] Models of Randall-Sundrum-type extra dimensions, where the Planck scale coupling is replaced by a TeV scale coupling of gravitons, suggest branching ratios of order $10^{-9}$ .[3]

Theories of infinite extra dimensions loosely predict a value of the branching ratio BR ~ $10^{-9}$. This value is bounded above at a level of BR ~ 4 x $10^{-9}$ by experimental searches for invisible decay of the Z boson. These searches suggest that any possible graviton coupling scale must be greater than about 2.7 TeV. BR is bounded below at ~$10^{-10}$ by a triviality argument – the graviton coupling scale in this theory must have an energy scale < 10 TeV to address the gauge hierarchy issue.

We investigated a “straw man” detector for the purposes of evaluating the feasibility of such an experiment. The detector consists of a radioisotope positron source ($^{22}$Na), a positron tagging system (including a high-resolution germanium detector), a moderator to form ortho-Ps (the long-lived Ps state), and a large volume liquid scintillator calorimeter. The signal in the experiment would be a tag signal for the emission of a positron, followed by the absence of the detection of the 1.022 MeV annihilation gammas in the calorimeter. Liquid organic scintillator was investigated because of the fast scintillation time: a high count rate is required to limit the data acquisition time. There is also substantial experience at LBNL and LLNL with such tank detectors. The source would need to be ~1 μCi to achieve a limit of BR < $10^{-8}$ in 100 days of operation.

Most positron emissions would be followed by detection of two 511 keV gammas in the calorimeter. The size of the calorimeter volume is determined by requiring the escape probability for the two photons to be less than ~$10^{-10}$. This is about 4 m in diameter, but would be considerably smaller for a denser (higher Z) scintillator such as BGO, LSO, or $LaCl_3$.

The tagging detector consists of two thin (0.5 mm) layers of plastic scintillator on one side of the source, and a single layer of thin scintillator and a Ge detector (subtending about 0.1□ solid angle) on the opposite side. A positron decay trigger consists of coincident events in the two-layer plastic scintillator and a detection of the 1274 keV daughter gamma in the Ge detector. The two-layer scintillator and the single layer veto scintillator in the opposite direction reject low energy electrons from Compton processes generated by the 1274 keV gamma. All of the scintillators would be read by two photomultiplier tubes in coincidence to reduce the single-tube dark count accidental rate. The tag signal occurs when a positron traverses both scintillator layers (and then enters the moderator), the gamma ray deposits full energy in the Ge detector, and there is no hit in the Compton veto detector.

Several background processes are insignificant at the desired level of sensitivity. These include radiobackgrounds (a worst case estimate of 1 false count from $^{14}$C in 100 d). The process (e+e- □ □□) has a branching ratio of $10^{-18}$. In the presence of other atoms, Ps can annihilate to a single photon or no photons, through annihilation and ejection of inner shell electrons. Although calculations and measurements of these processes are somewhat controversial, they have cross sections which scale strongly with atomic number, and the use of low-Z materials can reduce this background to a $10^{-12}$ branching ratio limit.

An irreducible source of background arises from the inner bremsstrahlung (IB) process during electron capture decay of the radioisotope source. In this process, the captured electron can radiate a gamma ray in addition to the trigger 1274 keV gamma. The energy spectrum of the IB gammas extends to the decay endpoint energy. The IB photons can Compton scatter, producing energetic (~ 1 MeV) electrons which easily trigger the positron tagging scintillators, resulting in a false trigger with no positron produced. With our “straw man” detector design, this results in a background at about BR = $10^{-6}$. Because any radioisotope source of positrons has an electron capture probability, the IB radiation is unavoidable. Any proposed experiment would require relocating the positron source outside the detector, and guiding positrons into the center of the calorimeter via a beamline. The trigger system could thus be shielded from radiation from the source. While not unfeasible, this positron beam technique presents more serious technical challenges.

## REFERENCES

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